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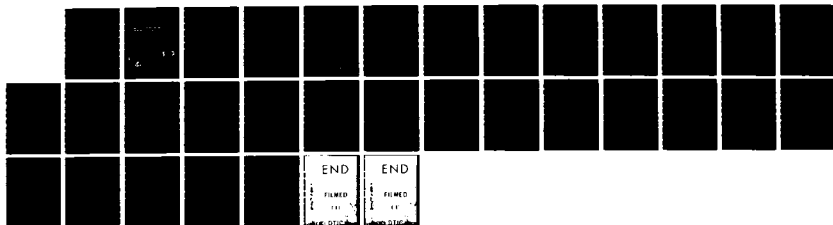
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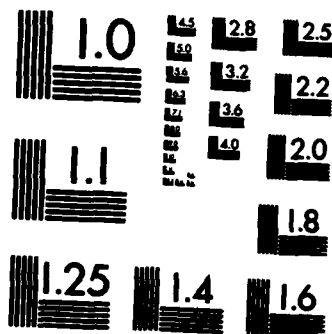
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HIGH SPACE HARMONIC PERTURBATIONS IN TRAVELLING WAVE TUBES

BY HAN S. UHM, JOON Y. CHOE,
CHUNG M. KIM

RESEARCH AND TECHNOLOGY DEPARTMENT

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FOREWORD

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I. INTRODUCTION

In recent years, there has been a growing interest in the millimeter and sub-millimeter microwave amplifiers such as the gyrotron,^{1,2} the relativistic magnetron³ and the free electron lasers.^{4,5} Moreover, in the last several decades, the theoretical and experimental investigation⁶⁻¹⁰ of the travelling wave tube has been extensively carried out. However, in order to upgrade the conventional travelling wave tube into the high power and high frequency tube, more rigorous investigation of the free streaming mode in an electron beam is required. In this regard, in this article we develop a theory of stability properties of the free streaming mode in an electron beam propagating through a tape helix waveguide, including high space harmonic perturbations. Particularly, properties of the high space harmonic perturbations are elaborately investigated, in connection with application on a high frequency microwave amplifier. This paper extends the previous self-consistent theory¹⁰ of the free streaming mode in a travelling wave tube, to higher values of space harmonic number.

The outline of the paper is the following: The dispersion relation of the free streaming mode either in a hollow beam or in a solid beam propagating through a tape helix waveguide is obtained in Sec. II, including high space harmonic perturbations. In Sec. III, stability properties of the free streaming mode in a tape helix travelling wave tube are numerically investigated for a broad range of physical parameters by making use of the dispersion relation. One of the most important features in this analysis is that the instability of the free streaming mode occurs at a very large value of microwave frequency for a high harmonic perturbation. In this regard, millimeter microwave can be easily attainable by reducing the helix radius to a subcentimeter and by making use of high space harmonic perturbations.

II. LINEAR THEORY OF THE FREE STREAMING MODE

The physical configuration consists of a relativistic solid or hollow electron beam that is infinite in axial extent and aligned parallel to a uniform applied magnetic field $B_0 \hat{e}_z$. The electron beam radius for either solid or hollow beam is denoted by R_0 . Cylindrical polar coordinates (r, θ, z) are introduced in the analysis. The electron beam is propagating through a helix tape with width δ and with zero thickness located inside a conducting waveguide with radius R_c . The radius and pitch of the helix are denoted by R_h and L , respectively, thereby defining the pitch angle and the unit helix vector \hat{e}_ϕ by

$$\cot \phi = 2\pi R_h / L \quad (1)$$

and $\hat{e}_\phi = \cos \phi \hat{e}_\theta + \sin \phi \hat{e}_z$ where \hat{e}_θ and \hat{e}_z are unit vectors in the azimuthal and axial directions. Moreover, in the present analysis, we assume $v/\gamma_b < 1$, where $v = N_b e^2 / mc^2$ is Budker's parameter, $N_b = 2\pi \int_0^{R_h} dr r n_b^0(r)$ is the number of electrons per unit axial length, $n_b^0(r)$ is the equilibrium electron density, c is the speed of light in vacuo, $-e$ and m are the electron charge and rest mass, respectively, and $\gamma_b mc^2$ is the characteristic electron energy in the laboratory frame. We also assume that the thickness of the annular electron beam is much less than its mean radius, i.e., $a \ll R_0$, where $2a$ is the characteristic thickness of the annular electron beam.

In the present analysis, we investigate stability properties of the free streaming mode for the choice of equilibrium distribution function

$$f_b^0(H, P_\theta, P_z) = \frac{\hat{n}_b \Delta}{2\pi^2 \gamma_b m} \frac{\delta(H - \omega_b P_\theta - \gamma_b mc^2)}{(P_z - \gamma_b m \beta_b c)^2 + \Delta^2} \quad (2)$$

or the solid beam and

$$f_b^0(H, P_\theta, P_z) = \frac{\omega_{cb} N_b \Delta}{4\pi^3 m c^2} \frac{\delta(\gamma - \hat{\gamma}) \delta(P_\theta - P_0)}{(P_z - \gamma_b m \beta_b c)^2 + \Delta^2} \quad (3)$$

for the hollow electron beam. In Eqs. (2) and (3), $H = \gamma m c^2 = (m^2 c^4 + c^2 p_z^2)^{1/2}$ is the total energy, $P_\theta = r \left[p_\theta - (e/2c) r B_0 \right]$ is the canonical angular momentum, $P_z = p_z$ is the axial canonical momentum, P_0 , \hat{n}_b , $\hat{\gamma}$ and Δ are constants.

For present purposes, the analysis is restricted to

$$|\Omega| = |\omega - (k + 2\pi s/L) \beta_b c| \ll 2\pi \beta_b c/L \quad (4)$$

where $\beta_b c$ is the mean axial velocity of beam electrons, ω and k are the eigenfrequency and the axial wavenumber, respectively, of the free streaming mode, and s is the space harmonic number. Making use of Floquet's theorem, we adopt a normal mode approach in which all perturbations are assumed to vary according to

$$\psi(x, t) = \sum_{n=-\infty}^{\infty} \hat{\psi}_n(r) \exp \{i(n\theta + k_n z - \omega t)\} \quad (5)$$

where

$$k_n = k - 2\pi(n-l)/L \quad (6)$$

is the axial wavenumber for the component n and l represents the primary azimuthal mode number. Making use of the linearized Vlasov-Maxwell Equations,¹⁰

the eigenvalue equation for the free streaming mode in a hollow electron beam is given by

$$\left\{ \frac{1}{r} \frac{\partial}{\partial r} r \frac{\partial}{\partial r} - \frac{n^2}{r^2} + \frac{\omega^2}{c^2} - k_n^2 \right\} \bar{E}_{zn}(r) = \begin{cases} -\frac{\delta(r-R_0)}{R_0} \sigma(\omega, k) \bar{E}_{zn}(R_0), & n = l - s, \\ 0, & \text{otherwise,} \end{cases} \quad (7)$$

for the perturbed axial electric field and

$$\left\{ \frac{1}{r} \frac{\partial}{\partial r} r \frac{\partial}{\partial r} - \frac{n^2}{r^2} + \frac{\omega^2}{c^2} - k_n^2 \right\} \bar{B}_{zn}(r) = 0, \quad (8)$$

for the perturbed axial magnetic field. In Equation (7), the source function $\sigma(\omega, k)$ is defined by

$$\sigma(\omega, k) = \frac{2v}{\gamma_b^3} \frac{k_n^2 c^2 - \omega^2}{(\omega - k_n \beta_b c + i |k_n| \Delta / \gamma_b^3 m)^2} \quad (9)$$

The physically acceptable solution to Equation (7) is¹⁰

$$\bar{E}_{zn}(r) = a_n \begin{cases} J_n(p_n r) + g(\omega, k) N_n(p_n r), & n = l - s, \\ J_n(p_n r), & \text{otherwise,} \end{cases} \quad (10)$$

for $R_0 \leq r \leq R_n$, where

$$g(\omega, k) = -\frac{J_\alpha(\zeta_\alpha) D(\omega, k)}{N_\alpha(\zeta_\alpha) F(\omega, k)}, \quad (11)$$

the integer α is defined by

$$\alpha = l - s, \quad (12)$$

$J_n(x)$ and $N_n(x)$ are the Bessel functions of the first and second kinds, respectively, of order n , a_n is a constant, and the parameter ζ_α is defined by

$$\zeta_\alpha^2 = p_\alpha^2 R_c^2 = (\omega^2/c^2 - k_\alpha^2) R_c^2 \quad (13)$$

In Equation (11), the vacuum dispersion function $D(\omega, k)$ is defined by

$$D(\omega, k) = \sum_n \frac{\sin(k_n \delta/2)}{k_n \delta/2} \left\{ \eta_n^2 \left(\tan \phi - \frac{k_n n}{\eta_n p_n} \right)^2 \frac{J_n(\eta_n)}{J_n(\zeta_n)} \right. \\ \times \left[J_n(\zeta_n) N_n(\eta_n) - J_n(\eta_n) N_n(\zeta_n) \right] \\ \left. + \frac{\omega^2 R_h^2}{c^2} \frac{J'_n(\eta_n)}{J'_n(\zeta_n)} \left[J'_n(\zeta_n) N'_n(\eta_n) - J'_n(\eta_n) N'_n(\zeta_n) \right] \right\} \quad (14)$$

and the function $F(\omega, k)$ is given by

$$F(\omega, k) = D(\omega, k) + \eta_\alpha^2 \tan^2 \phi \frac{\sin(k_\alpha \delta/2)}{k_\alpha \delta/2} \\ \times \frac{[J_\alpha(\zeta_\alpha) N_\alpha(\eta_\alpha) - J_\alpha(\eta_\alpha) N_\alpha(\zeta_\alpha)]^2}{J_\alpha(\zeta_\alpha) N_\alpha(\zeta_\alpha)}, \quad (15)$$

where the prime (') denotes $(d/dx) J_n(x)$ and $(d/dx) N_n(x)$, and the parameter η_α is detoned by $\eta_\alpha = \zeta_\alpha R_h/R_c$.

The axial electron field for the component $n = \alpha$ is given by

$$\hat{E}_{z\alpha}(r) = a_\alpha \begin{cases} [1 + g N_\alpha(p_\alpha R_0)/J_\alpha(p_\alpha R_0)] J_\alpha(p_\alpha r), & 0 \leq r \leq R_0, \\ J_\alpha(p_\alpha r) + g N_\alpha(p_\alpha r), & R_0 \leq r \leq R_h, \end{cases} \quad (16)$$

for the eigenvalue equation (7) of a hollow electron beam. Making use of the boundary conditions of $\hat{E}_z(r)$ at $r = R_0$, we obtain the dispersion relation of the free streaming mode

$$\Gamma_h(\omega, k) = \frac{2v}{\gamma^3 b} \frac{k_\alpha^2 c^2 - \omega^2}{(\omega - k_\alpha \beta_b c + i|k_\alpha| \Delta/\gamma_b^3 m)^2} \quad (17)$$

for the hollow electron beam. In Equation (17), the wave admittance of the hollow beam at the beam location is defined by

$$\Gamma_h(\omega, k) = -\frac{2}{\pi} \frac{g(\omega, k)/J_\alpha(p_\alpha R_0)}{J_\alpha(p_\alpha R_0) + g(\omega, k)N_\alpha(p_\alpha R_0)} \quad (18)$$

In a similar manner, we can show that the dispersion relation of the free streaming mode for the solid electron beam is given by¹⁰

$$\frac{\xi J'(\xi)}{J_\alpha(\xi)} = \Gamma_s(\omega, k), \quad (19)$$

where

$$\Gamma_s(\omega, k) = p_\alpha R_0 \frac{J'_\alpha(p_\alpha R_0) + g(\omega, k) N'_\alpha(p_\alpha R_0)}{J_\alpha(p_\alpha R_0) + g(\omega, k) N_\alpha(p_\alpha R_0)} \quad (20)$$

is the wave admittance at the beam surface and

$$\xi^2 = \left(k_\alpha^2 - \frac{\omega^2}{c^2} \right) \left[\frac{4\nu/\gamma_b^3}{(\omega - k_\alpha \beta_b c + i|k_\alpha| \Delta/\gamma_b^3 m)^2} - R_0^2 \right] \quad (21)$$

The dispersion relations of the free streaming mode in Equations (17) and (19) can be used to investigate gain and bandwidth of the traveling wave tube amplifier for a broad range of physical parameters.

III. STABILITY PROPERTIES OF FREE STREAMING MODE

Assuming no beam electrons ($v \rightarrow 0$), we obtain the vacuum dispersion relation

$$D(\omega, k) = 0 \quad (22)$$

from Equations (11) and (17) - (21). The vacuum dispersion function $D(\omega, k)$ in Equation (22) is defined in Equation (14). Even though the dispersion relation is a very complicated transcendental function of ω and k , in the limiting case where the outer conducting wall is very close to the helix (i.e., $R_c/R_h \rightarrow 1$), the vacuum dispersion relation is simplified to three distinctive relations.¹¹ These are the transverse electron like, the transverse magnetic like and the helix modes. Particularly, the helix mode is represented by a straight line

$$\omega = \pm [kc \sin\phi + \ell(c/R_c) \cos\phi] \quad (23)$$

in the (ω, k) parameter space. Figure 1 shows plots of the normalized frequency $\omega R_h/c \cos\phi$ versus the normalized axial wavenumber $k R_h \tan\phi$ obtained from Equation (22) for helix mode, $\phi = \pi/6$, $\delta/L = 0.3$, $R_c/R_h = 1.1$ and several values of the azimuthal mode number ℓ . Obviously from Figure 1, the dispersion curve of the helix mode for $R_c/R_h = 1.1$ is nearly a straight line as predicted in Equation (23).

The characteristic free streaming mode in the travelling wave tube is given by

$$\omega = k\beta_b c + (2\pi s/L)\beta_b c \quad (24)$$

from Equation (4). In this regard, we conclude from Equations (23) and (24) that a high frequency microwave amplifier can be developed by a choice of beam parameters satisfying

$$\begin{aligned} \beta_b &= \sin\phi \\ \ell &= s \end{aligned} \quad (25)$$

for $R_c/R_h \approx 1$. In obtaining Equation (25), use has been made of Equations (1), (23), and (24).

Stability properties of the free streaming mode $\omega = (k + 2\pi s/L)\beta_b c$ in an electron beam propagating through a tape helix waveguide is investigated, in connection with microwave amplifications. Making use of the fact that the "Doppler-shifted" eigenfrequency in Equation (4) is well removed from the free streaming mode, i.e., $|\Omega| \ll 2\pi\beta_b c/L$, and evaluating the wave admittance $\Gamma_h(\omega, k)$ in Equation (18) at $k = k_b = \omega/\beta_b c - 2\pi s/L$, the dispersion relation of the hollow electron beam in Equation (17) can be approximated by

$$\left[\Gamma_h(\omega, k_b) - \frac{1}{\beta_b c} \left(\frac{\partial}{\partial k} \Gamma \right)_{k_b} \Omega \right] \left(\Omega + i \frac{\omega \Delta}{\gamma_b^3 m \beta_b c} \right)^2 = \frac{2\nu\omega^2}{\gamma_b^5 \beta_b^2} \quad (26)$$

The growth rate $\Omega_i = \text{Im} \Omega$ and Doppler-shifted real frequency $\Omega_r = \text{Re} \Omega$ are numerically obtained from Equation (26) for a broad range of physical parameters. For present purposes, to illustrate the high frequency amplification, shown in Figure 2 are plots of the normalized growth rate $\Omega_i R_h/c$ versus $\omega R_h/c$ obtained from Equation (26) for the nonrelativistic hollow beam with $\nu = 0.001$ and $\phi = 0.4$, $R_0/R_h = 0.75$, $R_c/R_h = 1.1$, $\delta/L = 0.3$, $\Delta/\gamma_b m \beta_b c = 0.01$, and (a) $(\ell, s) = (2, 2)$, $\beta_b = 0.384$ and (b) $(\ell, s) = (7, 7)$, $\beta_b = 0.379$. As expected in Equations (24) and (25), the high frequency amplification is possible by increasing the space harmonic number s .

We conclude this section by presenting stability properties of the free streaming mode in a relativistic electron beam. Shown in Figure 3 is plots of the normalized growth rate $\Omega_i R_h/c$ versus $\omega R_h/c$ for $\phi = 0.8$, and (a)

(l,s) = (0,0), $\beta_h = 0.715$, (b) (l,s) = (10,10), $\beta_b = 0.716$ and (c) (l,s) = (20,20) $\beta_b = 0.716$, and parameters otherwise identical to Figure 2. Figure 3 repeatedly exhibits instability in a broad range of the parameter $\omega R_h/c$. Particularly, the instability occurs at a very large value of microwave frequency for a relativistic electron beam and a high space harmonic number s . For example, in Figure 3(c), instability occurs at $\omega R_h/c \approx 15$. In this regard, millimeter microwave can be easily attainable by reducing the helix radius to a subcentimeter. Brief investigation of stability properties of the free streaming mode in a solid beam has been carried out in a previous study¹⁰ by authors, and we urge the reader to review the reference 10 for numerical analysis of solid beam.

IV. CONCLUSIONS

In this paper, we have examined stability properties of the free streaming mode in an electron beam propagating through a tape helix waveguide, including influence of the high space harmonic perturbation (i.e., $|s| \geq 1$). Stability properties of the high space harmonic perturbations have been extensively investigated, in connection with application on a high frequency microwave amplifier. The dispersion relation of the free streaming mode in a tape helix waveguide was obtained in Section II. In Section III, stability properties of the free streaming mode were numerically investigated for a broad range of physical parameters by making use of the dispersion relation. One of the most important features in this analysis is that the instability of high harmonic perturbations occurs at a very large value of microwave frequency. In this regard, millimeter microwave can be easily attainable by reducing the helix radius to a subcentimeter.

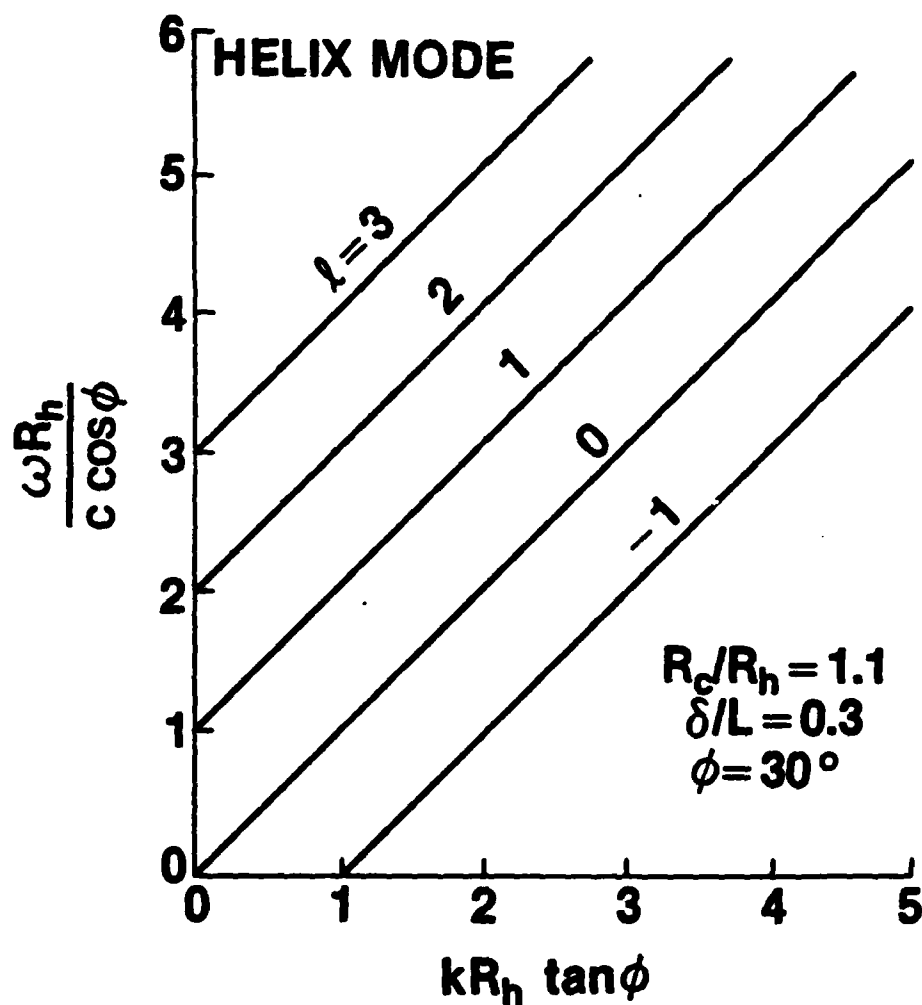


FIGURE 1. PLOTS OF NORMALIZED FREQUENCY $\omega R_h / c \cos \phi$ VERSUS NORMALIZED AXIAL WAVENUMBER $k R_h \tan \phi$ OBTAINED FROM EQUATION (22) FOR HELIX MODE, $\phi = \pi/6$, $\delta/L = 0.3$, $R_c/R_h = 1.1$ AND SEVERAL VALUES OF THE AXIMTHAL MODE NUMBER l .

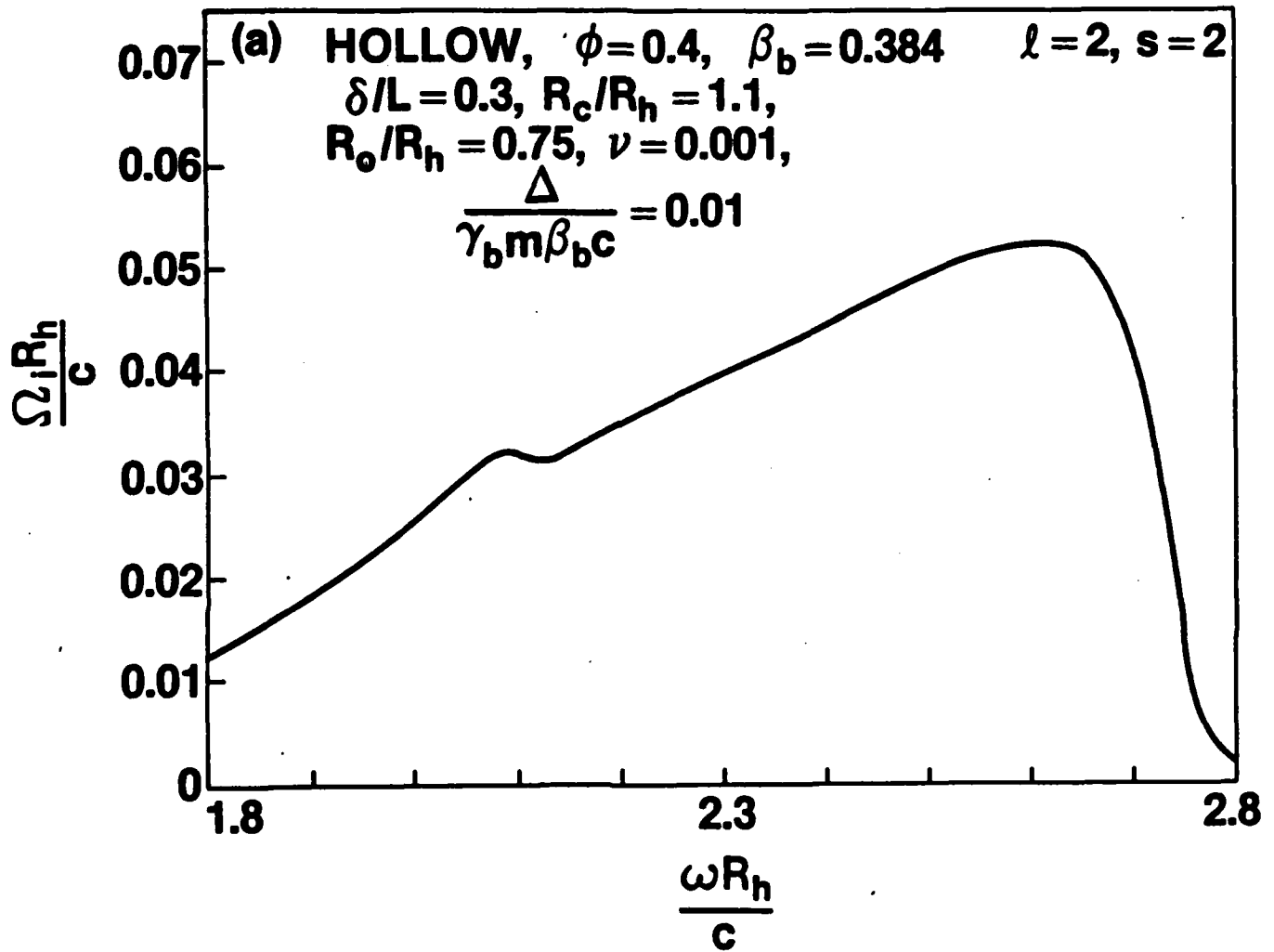


FIGURE 2 PLOTS OF NORMALIZED GROWTH RATE $\Omega_i R_h / c$ VERSUS $\omega R_h / c$ OBTAINED FROM EQUATION (26) FOR HOLLOW BEAM, $\nu = 0.001$, $\phi = 0.4$, $R_o/R_h = 0.75$, $R_c/R_h = 1.1$, $\delta/L = 0.3$, $\Delta/\gamma_b m \beta_b c = 0.01$, AND (a) $\beta_b = 0.384$ FOR $(l, s) = (2, 2)$ AND (b) $\beta_b = 0.379$ FOR $(l, s) = (7, 7)$.

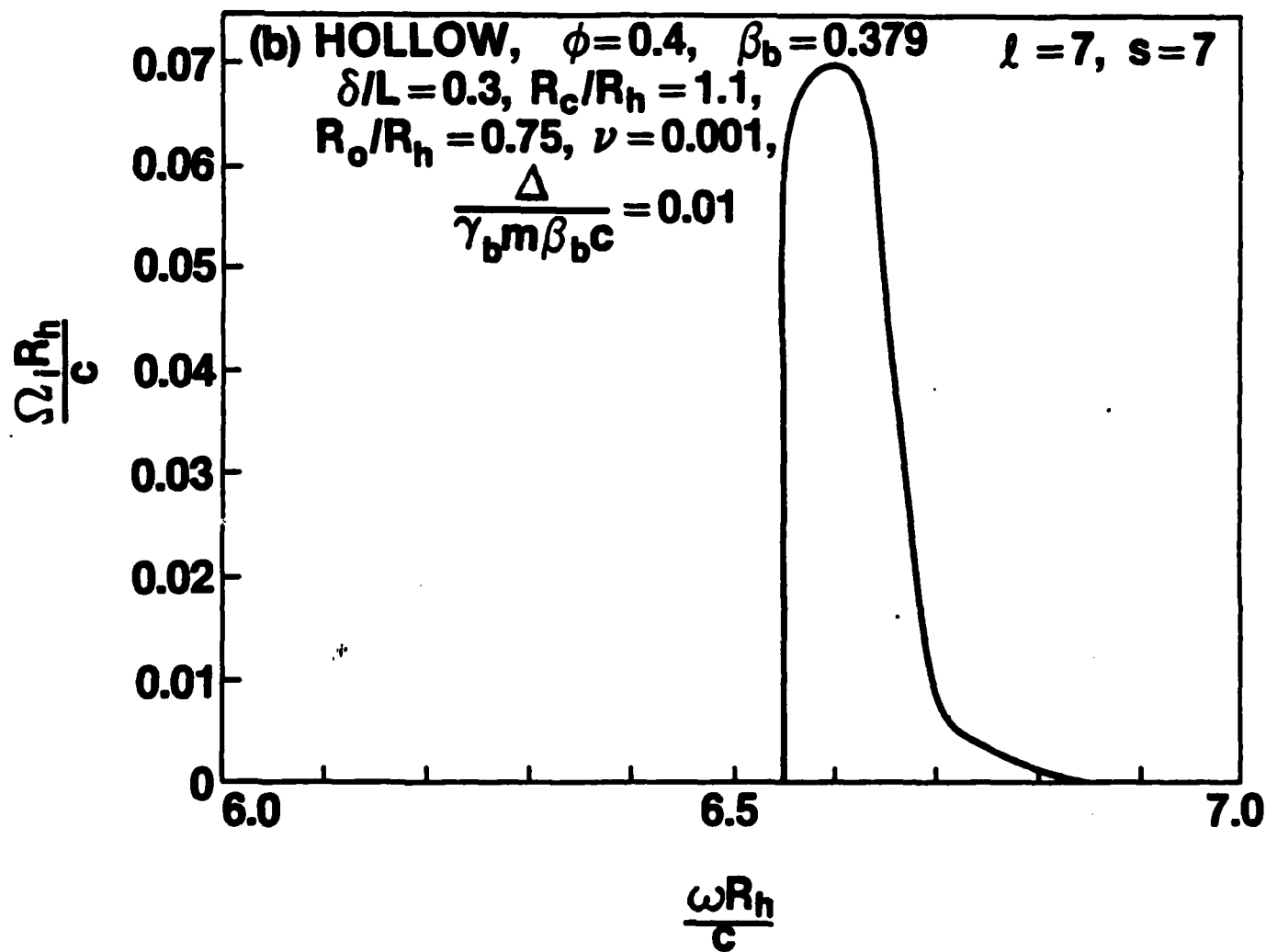


FIGURE 2. (CONTINUED)

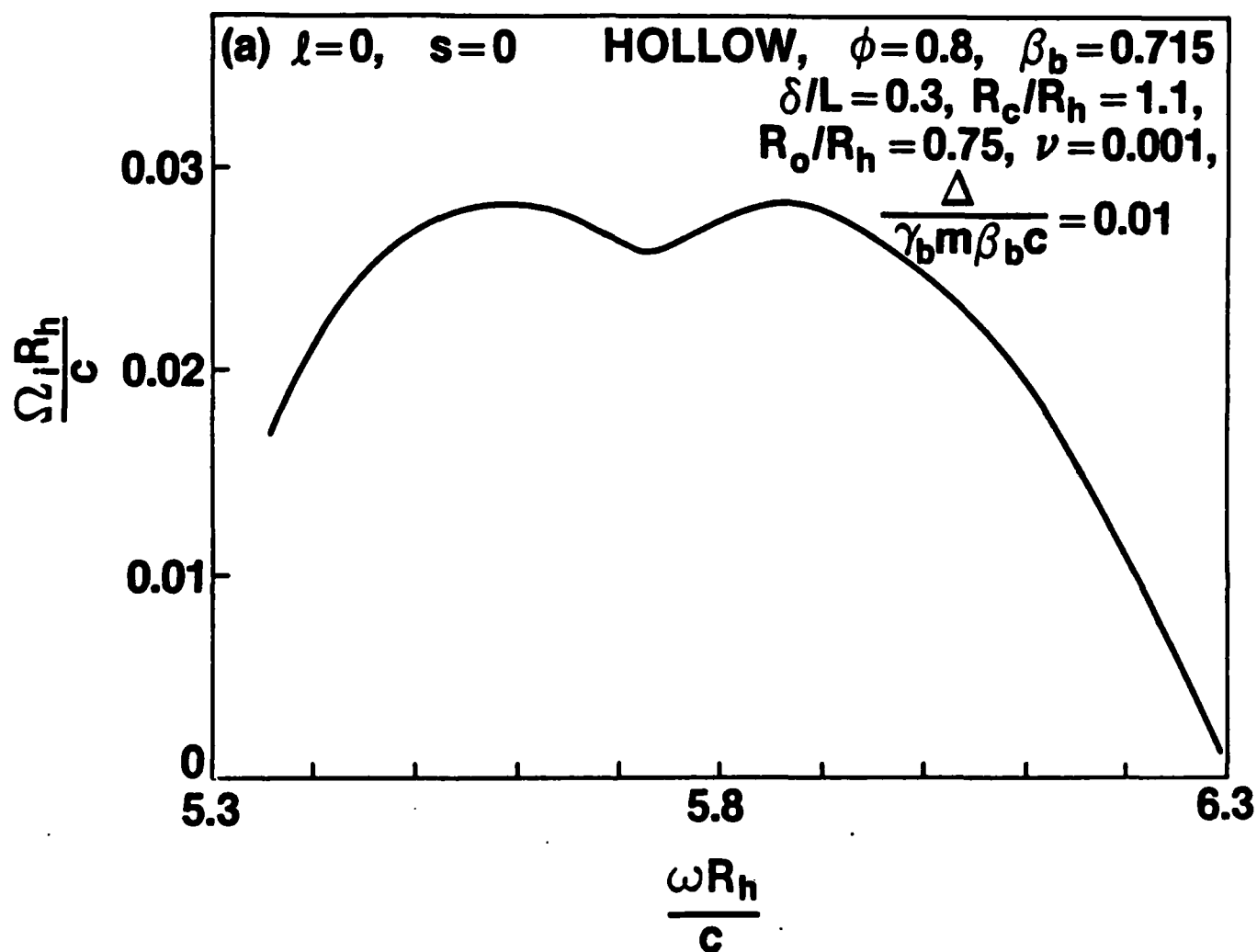


FIGURE 3. PLOTS OF NORMALIZED GROWTH RATE $\Omega_i R_h / c$ VERSUS $\omega R_h / c$ OBTAINED FROM EQUATION (26) FOR $\phi = 0.8$, (a) $\beta_b = 0.715$ FOR $(l,s) = (0,0)$, (b) $\beta_b = 0.716$ FOR $(l,s) = (10,10)$ AND (c) $\beta_b = 0.716$ FOR $(l,s) = (20,20)$, AND PARAMETERS OTHERWISE IDENTICAL TO FIGURE 2.

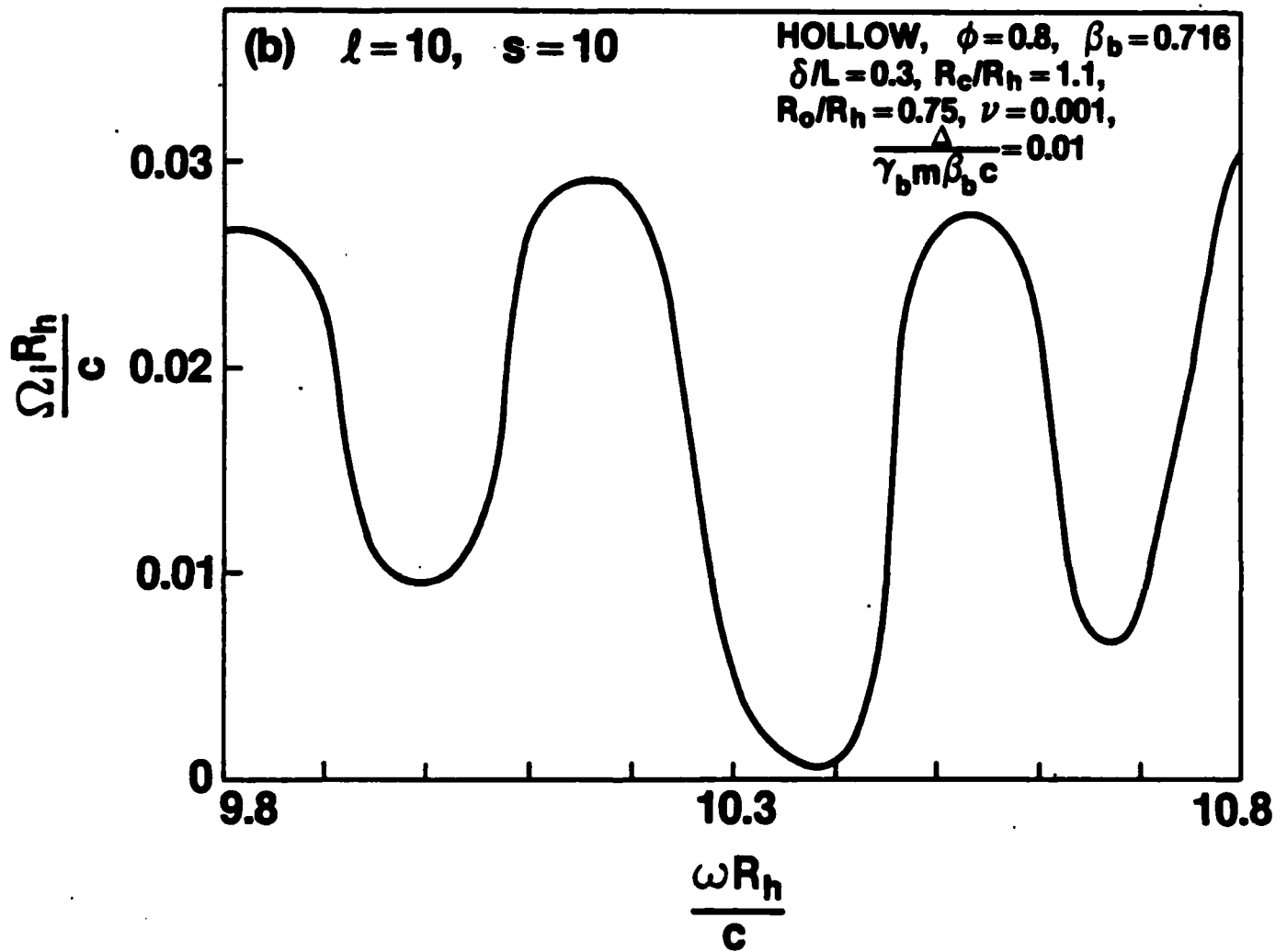


FIGURE 3. (CONTINUED)

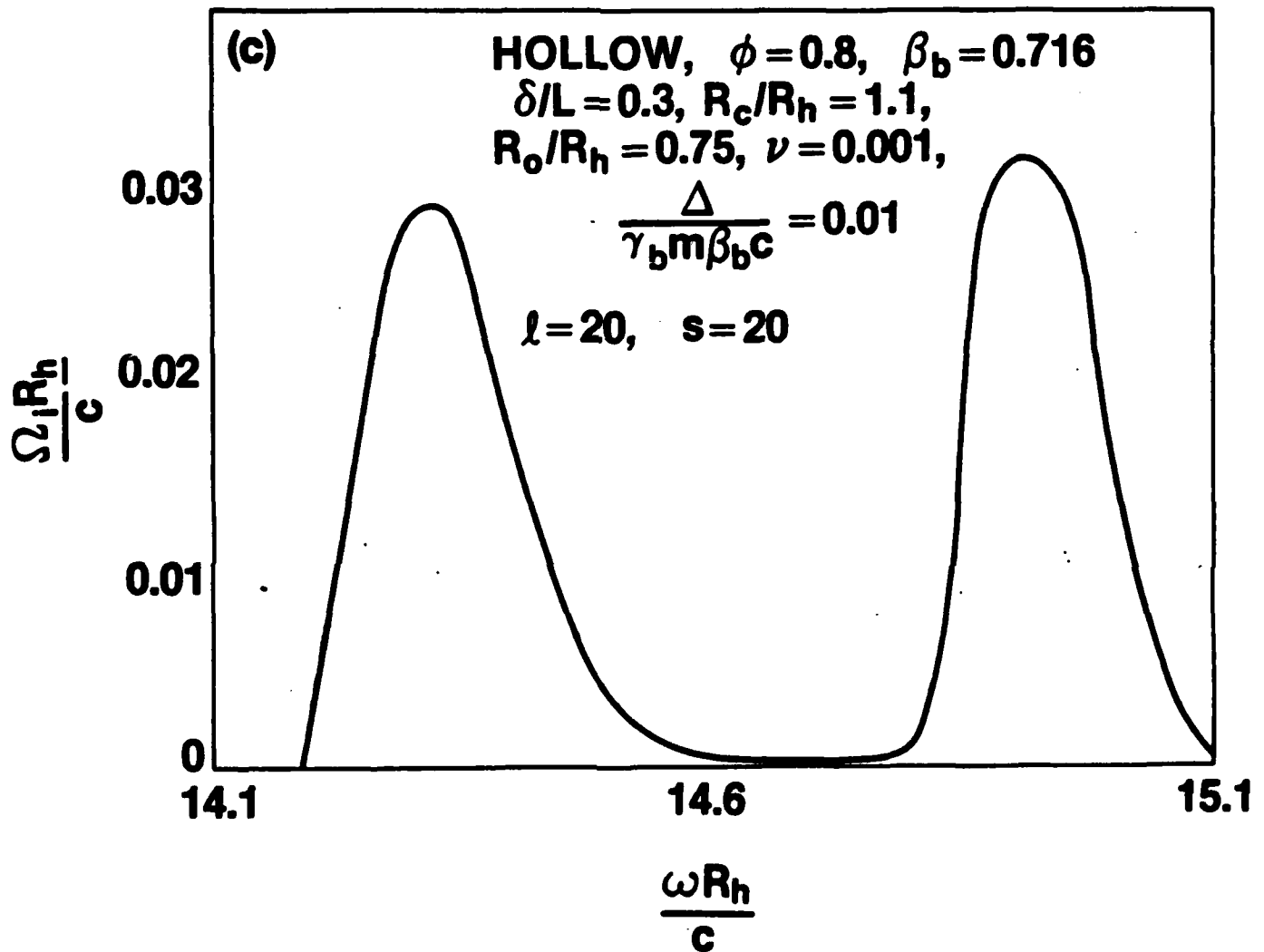


FIGURE 3. (CONTINUED)

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